

# Trojan capture by terrestrial planets

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**Abstract** The paper is devoted to investigate the capture of asteroids by Venus, Earth and Mars into the 1:1 mean motion resonance especially into Trojan orbits. Current theoretical studies predict that Trojan asteroids are a frequent by-product of the planet formation. This is not only the case for the outer giant planets, but also for the terrestrial planets in the inner Solar System. By using numerical integrations, we investigated the capture efficiency and the stability of the captured objects. We found out that the capture efficiency is larger for the planets in the inner Solar System compared to the outer ones, but most of the captured Trojan asteroids are not long term stable. This temporary captures caused by chaotic behaviour of the objects were investigated without any dissipative forces. They show an interesting dynamical behaviour of mixing like jumping from one Lagrange point to the other one.

**Keywords** Trojan capture · terrestrial planets · Near Earth asteroids · 1:1 mean motion resonance

## 1 Introduction

In February 1906, Max Wolf [38] discovered the first Trojan asteroid named 588 Achilles, after the hero of the Trojan war. Almost a century later, in 1990, the first Martian Trojan (5261 Eureka) was observed by Bowell et al. [4]. In 2001 the first Neptune Trojan was discovered by the Lowell Observatory Deep Ecliptic

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**Table 1** All observed Trojan asteroids in the inner Solar system.\* depicts an object which is only a candidate.

Name	a [AU]	e	i [deg]	motion Type
<b>Martian objects</b>				
5261 Eureka	1.523	0.065	20.3	$L_5$
1998 VF31	1.524	0.100	31.3	$L_5$
1999 UJ7	1.524	0.390	16.8	$L_4$
2007 NS2	1.524	0.054	18.6	$L_5$
1998 SD4	1.523	0.314	5.6	horseshoe
1998 QH56*	1.551	0.309	32.2	$L_5$
<b>Earth objects</b>				
2010 $TK_7$	1.000	0.191	20.880	$L_4$
2002 AA29	1.000	0.012	10.739	horseshoe
3753 Cruithne	0.998	0.515	19.811	horseshoe

Survey team (see Wasserman et al.[37]). Theoretical studies predict that Trojan asteroids are a frequent byproduct of planet formation and evolution. A simulation of the chaotic capture of Jupiter Trojans (Morbidelli et al. [26]) showed that about 3.4 Earth masses of planetesimals could be captured. Further investigations on the formation of (Trojan) planets in the 1:1 mean motion resonance (MMR), as a result of an interaction with the protoplanetary disk were done by Laughlin & Chambers [20], Beaugé et al. [1], Thommes [35], Cresswell & Nelson [6] and Lyra et al. [22]. Another important topic concerning the evolution, is the stability of such Trojan objects. Several authors have done dynamical studies for Trojan asteroids in the solar system (=SS) (e.g. Robutel [29], Marzari & Scholl [23], Dvorak et al. [11], Freistetter [14]). Some of these studies were dedicated to inclined Trojans (e.g. Schwarz et al.[32] and Dvorak & Schwarz[10]). An interesting topic is also the possibility of Trojan planets in extrasolar planetary systems like it is discussed e.g. in the dynamical investigations of Nauenberg [27], Érdi et al. [12], Dvorak et al. [9], and Schwarz et al. [33]. From the observational point of view we know approximately 5000 Jupiter Trojans, 7 Neptune Trojans in the outer Solar System, respectively 5 Martian Trojans (+1 candidate) and 2 co-orbital objects (horseshoe orbits) close to the Earth in the inner Solar System (shown in Table 1). Recently also an asteroid 2010  $TK_7$  has been observed, which librates around the leading Lagrange point  $L_4$  of the Earth (Connors et al. [5]). Calculations showed that the asteroid jump between  $L_4$  and  $L_5$ ; a so called "Jumping Trojan" which was found in the work of Tsiganis, Dvorak & Pilat-Lohinger [36].

For the origin of NEAs (e.g. Greenberg & Nolan [17] and [18]) it has been suggested that collisions in the main-belt continuously produce new asteroids by fragmentation of larger bodies. These fragments can be injected into the  $\nu_6$  and 3:1 MMR, which cause a change of their eccentricities and bring them into orbits intersecting the orbit of Mars (Marscrosser) and/or Earth (Earthcrossers, e.g. Milani et al. [24]). Farinella et al., [13] showed that bodies in the  $\nu_6$ , 3:1 or 5:2 MMR can have many collisions. Additional studies of the NEAs were done by Dvorak & Pilat-Lohinger [8] and Bottke et al. [3] who investigated their orbital distribution.

The most complete studies concerning the stability of Trojans of the planets in the SS have been undertaken by Mikkola & Innanen [25] and for the inner SS by Tabachnik & Evans [34], Brassier & Letho [2] and for Mars by Scholl & Marzari [30].

The work of Mikkola & Innanen [25] (a continuation of a series of papers by the same authors and also Zhang & Innanen [39]) dates back to the 1990 – with less computer facilities than we have today – but still provides important first results. They treated the problem of the stability of Trojans in the outer and inner SS; for the terrestrial planets they found that Mercury lose its Trojans within 1 Myrs, whereas Venus, Earth and Mars Trojans could survive up to 10 Myrs.

Tabachnik & Evans [34] confirmed partly the earlier results by Mikkola & Innanen [25] for Mercury, but they found orbits to survive up to 100 Myrs. These stable orbits were not tadpole orbits but all of them turned out to be on horseshoe orbits, in fact no long-lived Mercurian Trojans were found. Mercury, having by far the largest eccentricity shows the lowest probability of hosting Trojans.

The investigations of the Venus Trojan showed that none of them could survive for inclinations  $i > 16^\circ$ . Like for Venus also for Earth Trojans low inclined captured asteroids survived, but for the Earth a second possible stability zone opens between  $16^\circ < i < 24^\circ$ . The second window may disappear for longer integrations; for both planets some orbits may survive up to several Gyrs. For Mars low inclined asteroids do not survive, but bodies with inclinations in the range of  $14^\circ < i < 40^\circ$  move in orbits which could be stable for up to Gyrs. The instabilities are caused by secular resonances (=SR) seem to be responsible for ejections.

In their work Brasser & Letho [2] carefully checked the role of SR for high inclined Trojan asteroids. They found that the Kozai resonance with Jupiter (acting for  $i > 16^\circ$ ) leads to instability; in addition many SR between the terrestrial bodies have a destabilizing effect. Nevertheless they could confirm that the Trojan regions of Venus and Earth are long-term stable for low inclinations. The trapping into a SR is in the order of only 0.1 Myrs for Mercury but for the other planets about 1 Myrs.

Scholl & Marzari [30] studied the Mars Trojans with the aid of the frequency analysis. Due to the SR the low inclined region is depleted within Myrs, and stable regions exist for inclinations  $15^\circ < i < 30^\circ$ , where also the discovered Mars Trojans are moving.

According to these results we decided to investigate the capture into 1:1 MMR in the inner SS except Mercury with special emphasis temporary captures into Trojan motion.

## 2 Model and methods of investigation

The aim of this work is different from former studies which wanted to establish stable zones of Trojans of the planets. We investigated the capture of small bodies into the 1:1 MMR with the planets Venus, Earth and Mars. Therefore we did N-body simulations in a simplified dynamical model, which consists of Venus, Earth, Mars, Jupiter and Saturn up to 10 Myrs. Mercury was excluded from our computation because this planet does not seem to be able to host long lived Trojans (Tabachnik & Evans [34]) and the inclusion of Mercury would slow down the speed of the computation significantly; this means that the needed computer time would be increased significantly. We used the Lie-method with an automatic step-size control to solve the equations of motion (Hanslmeier & Dvorak [19], Delva [7], Lichtenegger [21]). The massless asteroids were placed in 3 different regions, which represent almost the whole region of the NEAs:

- Region A:  $0.72 < a < 0.98$  ( $\sim$  Atens)
- Region B:  $1.02 < a < 1.50$  ( $\sim$  Apollos)
- Region C:  $1.54 < a < 2.20$  ( $\sim$  Amors, and the main belt group Hungarias)

The sorting of the NEAs into different groups was introduced by Shoemaker et al. [31]. Milani et al. [24] classified the asteroids according to their collision probabilities and close encounters, whereas Freistetter [14] used methods from Fuzzy Logic.

In our studies we distributed 100 asteroids uniformly in the three different regions defined above. The initial eccentricities were set close to the planet's eccentricity and higher ( $e=0.1$  and  $e=0.2$ ). The choice of the other initial conditions was a random one: because we did the integrations starting with  $e=0.1$  (close to Mars  $e=0.098$ ) we used for the other elements initially (all the angles) the ones of Mars. We are aware that this choice is more or less artificial but during the integration of  $10^7$  years this choice does not seem to make big differences statistically. In Fig. 4 we show that for the initial conditions ( $e=0.1$  or  $e=0.2$ ) the distribution of eccentricities is very similar for both at the end of integration (with a peak at  $e=0.25$ ) and the bodies achieve large eccentricities. We started from almost plane orbits up to large inclinations; thus we have chosen the following initial values:  $i=1^\circ, 4^\circ, 9^\circ, 16^\circ, 25^\circ, 30^\circ$  and  $36^\circ$ . Because we did not find any captures for  $i = 36^\circ$  we made an additional run for  $i = 30^\circ$ . All in all (test computations included) some ten-thousand orbits of the asteroids were computed. The analysis of the data showed that we have to distinguish between different types of captures (see Figs. 2 and 3):

1. Satellite orbits
2. Tadpole orbits ( $L_4$  or  $L_5$ )
3. Jumping Trojans<sup>1</sup>
4. Horseshoe orbits

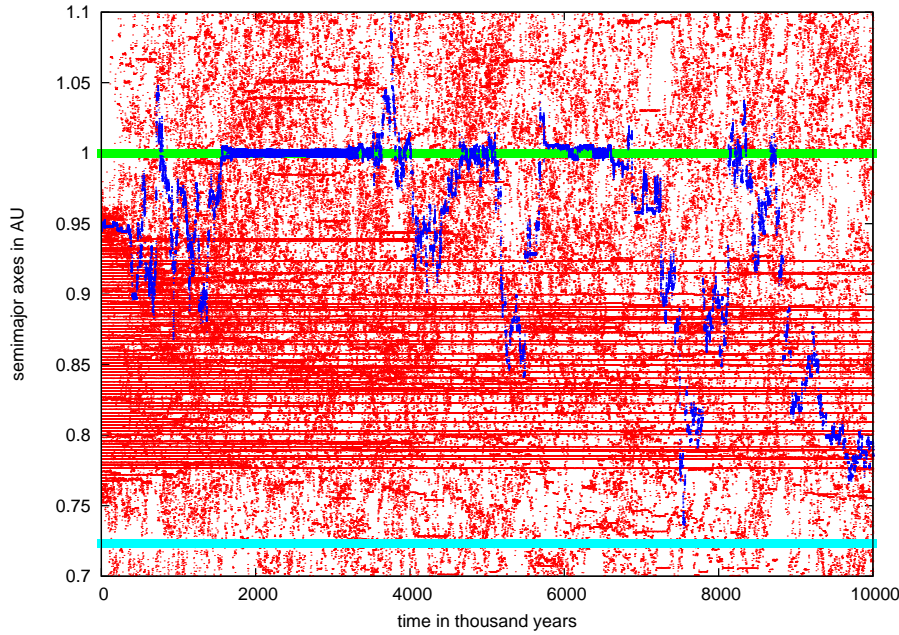
During our studies we found several single and multiple captures (can happen for one object). In case of multiple captures we observed a sort of mixing, between the different types of captures: jumping from one Lagrange point to the other, developing from a tadpole to a horseshoe orbit and vice-versa, transiting from horseshoe orbits to satellites of the planet and vice versa. The classification was done by checking the libration width  $\sigma$  which is defined as the difference between the mean longitude of the asteroid and the planet (Venus, Earth or Mars) ( $\lambda - \lambda_P$ ).  $\lambda, \lambda_P$  are given by  $\lambda = \varpi + M, \lambda_P = \varpi_P + M_P$  where  $\varpi, \varpi_P$  are the longitudes of the asteroid and of the planet and  $M, M_P$  are the mean anomaly of the asteroid respectively of the planet.

### 3 Results

In Fig. 1 we depict as one example the dynamical evolution of 100 fictitious bodies in region A with initial condition  $e=0.2$  and  $i=0.1$ . There are two candidates visible for captures by the Earth, one very short one ( $T \sim 9.6 \text{ Myrs}$ ) and one very long one ( $1.8 \text{ Myrs} < T < 4 \text{ Myrs}$ ), where all different kinds of captures may occurred.

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<sup>1</sup> The asteroids jump from  $L_4$  to  $L_5$  or vice versa, Tsiganis et al. [36]

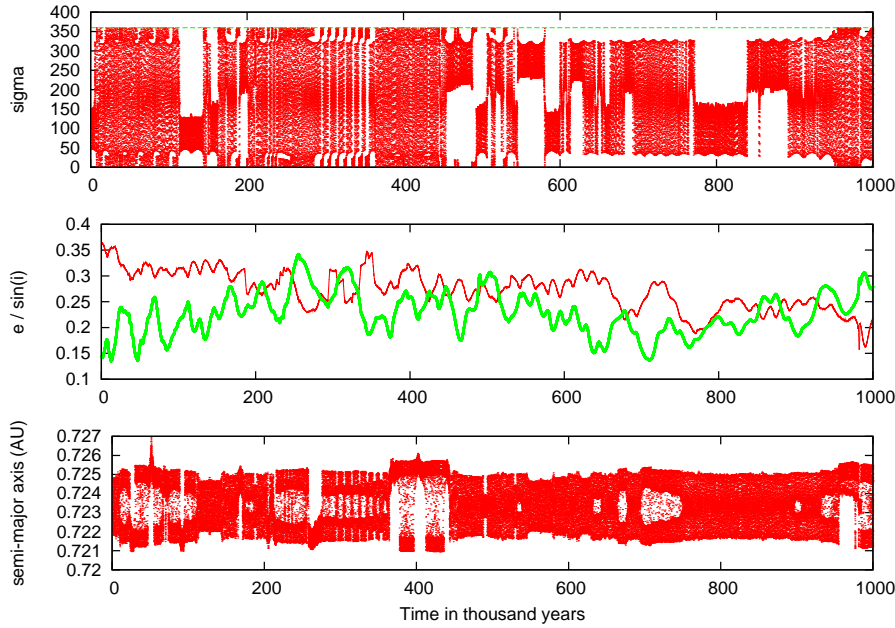


**Fig. 1** Example of one of the runs for the region A where 100 asteroids were located between Venus and Earth. We show the dynamical evolution of the semimajor axes of celestial bodies for 10 Myrs. Venus' and Earth's semi-major axes are just straight lines for  $a=0.72$  AU and  $a=1$  AU

We will discuss in more detail the verified captures which are presented Fig. 2 in the next paragraph. The capture candidates by Venus are visible for two short intervals of time ( $1.8 \text{ Myrs} < T < 1.9 \text{ Myrs}$  and  $4.6 \text{ Myrs} < T < 5 \text{ Myrs}$ ) by two different asteroids. There are some other interesting features like long straight lines for the whole time interval – just stable orbits in the region A – and other captures into MMR where the semi-major axis jumping and stay close for quite a long time; one is well visible for  $a_{ini} = 0.925$  AU for  $T \sim 6.3$  Myrs. Other such captures into high order MMR are visible for orbits outside the orbit of the Earth (e.g.  $a=1.05$  AU for  $1.8 \text{ Gyrs} < T < 4 \text{ Myrs}$ . ) and inside the orbit of Venus and Earth (e.g.  $a=0.5$  AU for  $8.0 \text{ Myrs} < T < 8.5 \text{ Myrs}$ ).

Fig. 2 shows the multiple events of the dynamical evolution of one asteroid captured by Venus and present the different cases of captures (mixed capture). In the upper panel of Fig. 2 the libration angle is depicted for 1 Myrs. The body is captured approximately after 0.13 Myrs, leaves then the region around  $L_4$  for about 0.05 Myrs but is captured very soon after again for several thousand years with a slightly larger libration. Close to 0.2 Myrs the fictitious asteroid is captured around  $L_5$ . After about 0.42 Myrs the asteroid jumps from one libration point to the other one. Around 0.8 Myrs the jumps happen in the other direction, namely from  $L_5$  to  $L_4$  which ends around 0.9 Myrs with a horseshoe orbit. Transient capture for being a satellite are only for short time of several thousand years (e.g. around 0.19 Myrs). The inclination (middle panel) varies between  $5^\circ < i < 20^\circ$  whereas the eccentricity is relatively large and changes between  $0.15 < e < 0.35$ .

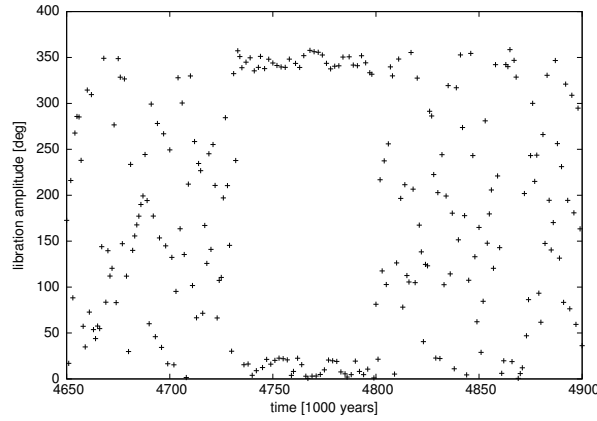
Evidently there is no correlation between these two orbital elements, which is quite contrary to planetary orbits where the angular momentum forces such a correlation; note that the fictitious asteroid is regarded as having no mass. The orbital elements ( $e$ ,  $i$  and  $a$ ) do not show whether the body is captured in a Trojan configuration. The discussion of the libration angle shows for the different types of captures the following characteristics: for the satellite type  $\sigma$  is around  $0^\circ$ , for  $L_4$   $\sigma \approx 60^\circ$ , for  $L_5$   $\sigma \approx 270^\circ$ . For horseshoe type the amplitude of the libration width is larger  $\Delta\sigma \approx 300^\circ$ , resulting in an orbit where the asteroid passes  $L_4$ ,  $L_3$  and  $L_5$  or vice versa, as well as the jumping Trojans.



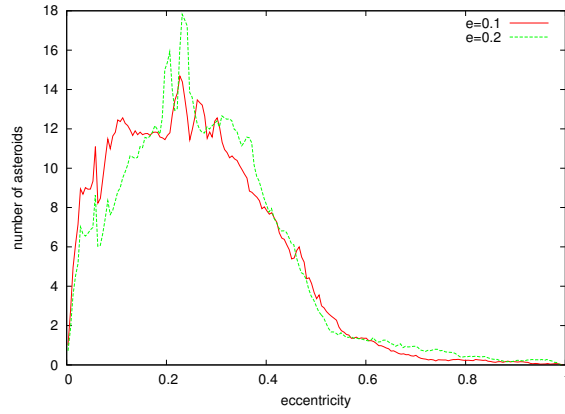
**Fig. 2** Dynamical evolution of an asteroid captured by Venus: the libration angle  $\sigma$  (upper panel), the eccentricity (green line), starting as lower line 0.15) and the inclination given in values of  $\sin(i)$  (red line) (middle panel) and the semi-major axis for 1 Myrs (lower panel); for a detailed description see the text.

The captures from the other planets show quite a similar dynamical behaviour. But we must say that a capture by a terrestrial planet is not a frequent phenomenon, however, our results have shown that only 35 captures of all captures (total captures are 77) in the inner SS are not mixed. Details of the different planets are shown in Table 2, where we can see that approximately one third of all captures are not mixed for the planets Venus and Earth, whereas for Mars the half of all captures are not mixed.

We conclude that these captured objects are very chaotic: it is not possible to reproduce a capture starting from the time just before the capture happens. Integrating 100 fictitious asteroids – as we have done it – results in many changes of the stepsize because one of the bodies may be close to a planet choosing a small



**Fig. 3** Dynamical evolution of the libration angle  $\sigma$  of an asteroid captured by Venus into a satellite configuration.



**Fig. 4** Distribution of the maximum eccentricities of the fictitious asteroids with initial values  $e = 0.1$  (red line) and  $e = 0.2$  (green line) during their dynamical evolution

**Table 2** Comparison of the total number of captures and the mixed captures in the inner Solar system.

Planet	total capture	not mixed capture
Venus	21	10
Earth	44	18
Mars	12	7
All	77	35

stepsize<sup>2</sup>. This leads to different accumulation of errors which propagate quite fast in a chaotic domain for different integrations when one repeats it from a later time; slightly different initial conditions. It means that the 'capture window' is quite small, but still large enough to allow many of them.

<sup>2</sup> we use an automatic stepsize control and it is the same for all involved celestial bodies

**Table 3** Asteroid captures from region A for Venus (V), Earth (E) and Mars (M); the initial eccentricity of the fictitious body is given in parenthesis.

incl(deg)	V(0.1)	V(0.2)	E(0.1)	E(0.2)	M(0.1)	M(0.2)
1	1	2	1	2	-	-
4	2	1	2	1	-	-
9	2	-	8	-	1	-
16	3	-	4	2	1	-
25	3	2	1	5	-	-
30	2	1	3	3	2	-
36	-	-	-	-	-	-

**Table 4** Asteroid captures from region B for Venus (V), Earth (E) and Mars (M); the initial eccentricity of the fictitious body is given in parenthesis

incl(deg)	V(0.1)	V(0.2)	E(0.1)	E(0.2)	M(0.1)	M(0.2)
1	1	-	2	-	-	-
4	-	-	1	-	2	-
9	-	1	1	-	-	1
16	-	-	1	1	-	-
25	-	-	-	-	-	-
30	-	-	2	4	2	2
36	-	-	-	-	-	-

As mentioned before we used for our simulations 4200 particles which were distributed over all three regions (region A, B and C). Our results have shown that from the 4200 asteroids 77 individual asteroids were captured into co-orbital motion. In total we measured 205 capture events, because of the former mentioned mixed capture. 59 capture events were measured close to  $L_4$  and 61 close to  $L_5$ . Comparable capture events were found in horseshoe motion (52 captures), 24 capture events were found in satellite motion and 9 events happens for jumping Trojans. A summary of the captures for the different planets are shown in Table 2. There we can see that approximately one third of all captures are not mixed for the planets Venus and Earth, whereas for Mars half of all captures are not mixed.

We found 3 jumping Trojans for the Earth, which is in a good agreement with the recent work of Connors et al. [5] who observed a  $L_4$  Trojan. Their calculations showed that the orbit of 2010  $TK_7$  is at least stable for 10000 years, which is again in good agreement with our studies. In addition they computed the orbit of this Trojan asteroid in the past and found a 'jump' from  $L_5$  libration to the present  $L_4$  libration at AD 400. In our work we located 4 asteroids for Venus, 3 for Earth and 2 for Mars to be captured as jumping Trojans.

In a next step we wanted to show which 'preferred' initial conditions lead to a capture into 1:1 MMR. Details are shown in the Tables 3 and 4 separately for the region A and region B. They are summarized in Fig. 5 for the planets Venus (upper graph), Earth (middle graph) and Mars (lower graph). In case of Venus most captures come from region A (19) and only 2 captures from region B. Also Earth captured most asteroids from region A (32) and several from region B (12). The capture of the Martian co-orbitals can be observed from all regions: Region A (4), Region B (7) and Region C (1). Further investigations have to be done to study more in detail the influence from the outer main belt, which will possibly change the capture probability of Mars. Many captures were found for large initial inclinations  $i_{ini}$  up to  $30^\circ$ , but we did not find any captures for  $36^\circ$ .



We also examined the eccentricity and the inclination at the time of a capture. These results are presented in Fig. 6 including the capture time of the first capture. We call that first capture, because in case of mixed capture more captures can happen. We distinguished between capture times smaller and larger than 1 Myrs. Our investigations showed that the planetesimals which were started close to a planet, will be captured earlier (first capture  $< 1 \text{ Myrs}$ ). This statement agrees quite well in case of Venus and Earth, where all planetesimals which were captured are within an initial distance to the planets of  $a < 0.2 \text{ AU}$ . However for Mars there is no agreement, because of the longer time interval up to the first capture Fig. 6 (lower panel). The Earth is presented in Fig. 6 middle graph, which shows that most captures are for asteroids initially close to the planet (presented as black circles in the graph) also visible in the initial condition diagramm of Fig. 5 (middle graph). In case of Venus we have only 1 close capture and for Mars we have 3 close capture, because the captures are distributed (as mentioned before). Furthermore we can conclude that all captures happen in the orbital parameter-space:  $0.15 < e_{\text{capture}} < 0.45$  and  $3^\circ < i_{\text{capture}} < 32^\circ$ .

Another important issue is the stability of the captured asteroids. We found out that the most stable objects are captured asteroids starting close to Mars with low initial inclinations ( $i = 9^\circ$ ). The maximum and the mean duration of the captured asteroids into stable co-orbital motion for:

1. Venus was  $6.3 \cdot 10^5$  years (mean value  $1.8 \cdot 10^5$  years),
2. Earth  $6.5 \cdot 10^5$  years (mean value  $1.6 \cdot 10^5$  years)
3. Mars  $2.9 \cdot 10^6$  years (mean value  $3.4 \cdot 10^5$  years).

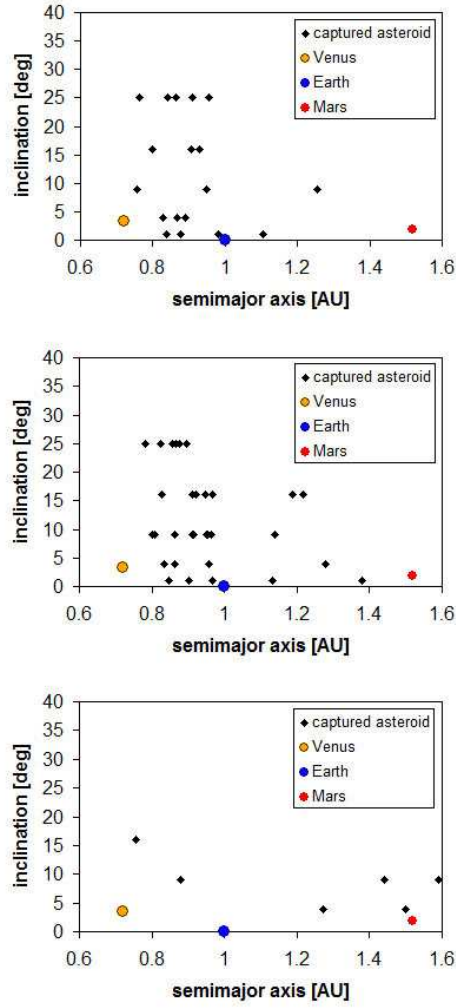
Only three captured objects were still stable after the computations of the orbits for 10 Myrs, two close to Earth and one close to Mars. The latter one is the most stable asteroid being captured into a horseshoe motion after 7.1 Myrs and stays there 2.9 Myrs up to the end of the integration (10 Myrs).

### 3.1 Comparison of the capture efficiency in the inner and outer Solar system

The capture efficiency in the outer SS was studied by Morbidelli et al. [26] in the case of Jupiter Trojans and by Nesvorný & Vokrouhlický [28] for the Neptune Trojans, by using the Nice model. The Nice model was designed for the investigation of the early evolution of the outer SS. In this model, the giant planets are assumed to have formed in a compact configuration (5-18 AU). Thus these studies consider also the interaction of the planetesimal disk with the planets, which induces a slow migration of the giant planets. We want to remark that our model is a simple n-body integration without any gravitational influence from the asteroid on the planets. Nevertheless, we compared our capture efficiency with the former mentioned studies. The capture efficiency<sup>3</sup> is given in Table 5 ordered by the distance to the Sun.

With this overview we can conclude that the capture probability in the inner SS is higher than in the outer one, especially taking into account that in the Nice model nongravitational forces were also included in their integration which possibly enlarged the number of captured Trojans (as presented in Table 5).

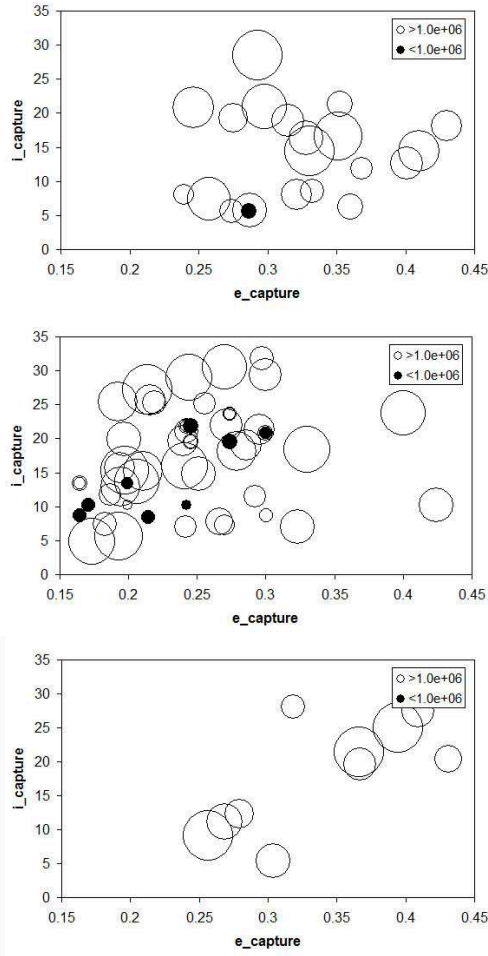
<sup>3</sup> The capture efficiency is defined per particle in the whole initial parameter space like in Nesvorný & Vokrouhlický [28] and Morbidelli et al. [26].



**Fig. 5** Initial orbital elements semimajor axis versus the inclination of the captured asteroids by Venus (upper graph), the Earth (middle graph) and by Mars (lower graph).

#### 4 Conclusions

Up to now several simulations were done for the outer SS, to show the capture of asteroids into co-orbital motion during the time when the giant planets migrated. We focused our work on the capture of co-orbital objects in the inner SS. In our studies we found several captures of asteroids into: tadpole (including  $L_4$ ,  $L_5$  Trojans and jumping Trojans), horseshoe and satellite motion for all three planets Venus, Earth and Mars. The studies up to now undertaken for the terrestrial planets deal primarily with the stability of samples of fictitious bodies already in a 1:1 MMR with a planet to establish stable regions around the equilateral equilibrium points. Normally these computations were stopped after the escape from the reso-



**Fig. 6** Mean orbital elements (eccentricity and inclination) just before the capture into the co-orbital motion by Venus (upper graph), the Earth (middle graph) and by Mars (lower graph). We distinguished between a capture time which is smaller and larger than 1 Myrs. The largeness of the circles shows whether the capture time is large or not.

nance. Our goal was a different one: we started from outside (or inside) the planets orbit away from the 1:1 MMR and checked for respective captures. Because these asteroids are on the edge of the stability region the 'stability times' (the state when they are in the phase of being coorbital with the planets) are sometimes very small (see Fig. 6). We can conclude from our results that the capture probability in the inner SS is higher than in the outer SS (205 capture events), but the asteroids are not long-term stable (Tabachnik & Evans [34]). Nevertheless, the capture window is limited by  $0.15 < e_{\text{capture}} < 0.45$  and by  $3^\circ < i_{\text{capture}} < 32^\circ$ , which is valid for all three planets.

In fact the mean values for the eccentricities of the three groups of the NEAs are close to the highest value of  $e=0.45$  in our investigation (compare with Fig.6).

**Table 5** Comparison of the capture efficiency from the inner Solar and the outer solar system.

Planet	capture efficiency
<b>inner solar system</b>	
Venus	$4.3 \cdot 10^{-3}$
Earth	$1.05 \cdot 10^{-2}$
Mars	$2.4 \cdot 10^{-3}$
<b>outer solar system</b>	
Jupiter	$2 \cdot 10^{-5}$
Neptune	$3 \cdot 10^{-4}$

**Table 6** The mean, minimum and maximum values of the orbital elements  $e$  and  $i$  for the different groups of NEAs. The data was taken from the Minor Planet Center August 2011).

Region	eccentricity	inclination [deg]
<b>Atens</b>		
mean value	0.35	13.67
minimum	0.01	0.00
maximum	0.90	56.10
<b>Apollos</b>		
mean value	0.52	13.71
minimum	0.03	0.00
maximum	0.97	154.50
<b>Amors</b>		
mean value	0.42	14.27
minimum	0.01	0.10
maximum	0.74	131.80

For the inclinations the mean value of the NEAs coincides with the mean value for the captured Trojans (Tab. 6).

All the captures we found are transient events; the probability of such a captured asteroids located initially between the terrestrial planets with moderate eccentricities and inclinations is surprisingly high. We explain it that after an integration time of about 1Myrs the eccentricities reach large values comparable to some of the discovered real Trojans of Mars (like 1999 UJ7).

We detected several multiple capture events showing a mixing of captures. That means they into different kinds of co-orbital motion. This could be confirmed in the work of Galiazzo & Schwarz [16] which was dedicated to investigate this mechanism from the Hungaria family. Especially interesting are the quite often observed jumping objects from one Lagrange point to the other. The first jumping Trojan was reported by Tsiganis et al. [36] for the Jupiter Trojan *Thersites* and recently observed by Connors et al. [5] for the Earth Trojan 2010 *TK*<sub>7</sub>. These very peculiar orbits need to be studied in more details not only for SS bodies but also in simplified dynamical models (e.g. the restricted three-body problem), which is an ongoing work.

**Acknowledgements** R. Schwarz and R. Dvorak wants to acknowledge the support by the Austrian FWF Project P 18930-N16. Special thanks to V. Eybl and Á. Bzszó who helped to improve the paper.

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